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STABILITY MEASUREMENTS OF ALUMINUM-STABILIZED NbTi AND BRONZE MATRIX Nb_3Sn POTTED SUPERCONDUCTING MAGNETS

by

D. J. Waltman, M. J. Superczynski
and F. E. McDonald

PROPULSION AND AUXILIARY SYSTEMS DEPARTMENT
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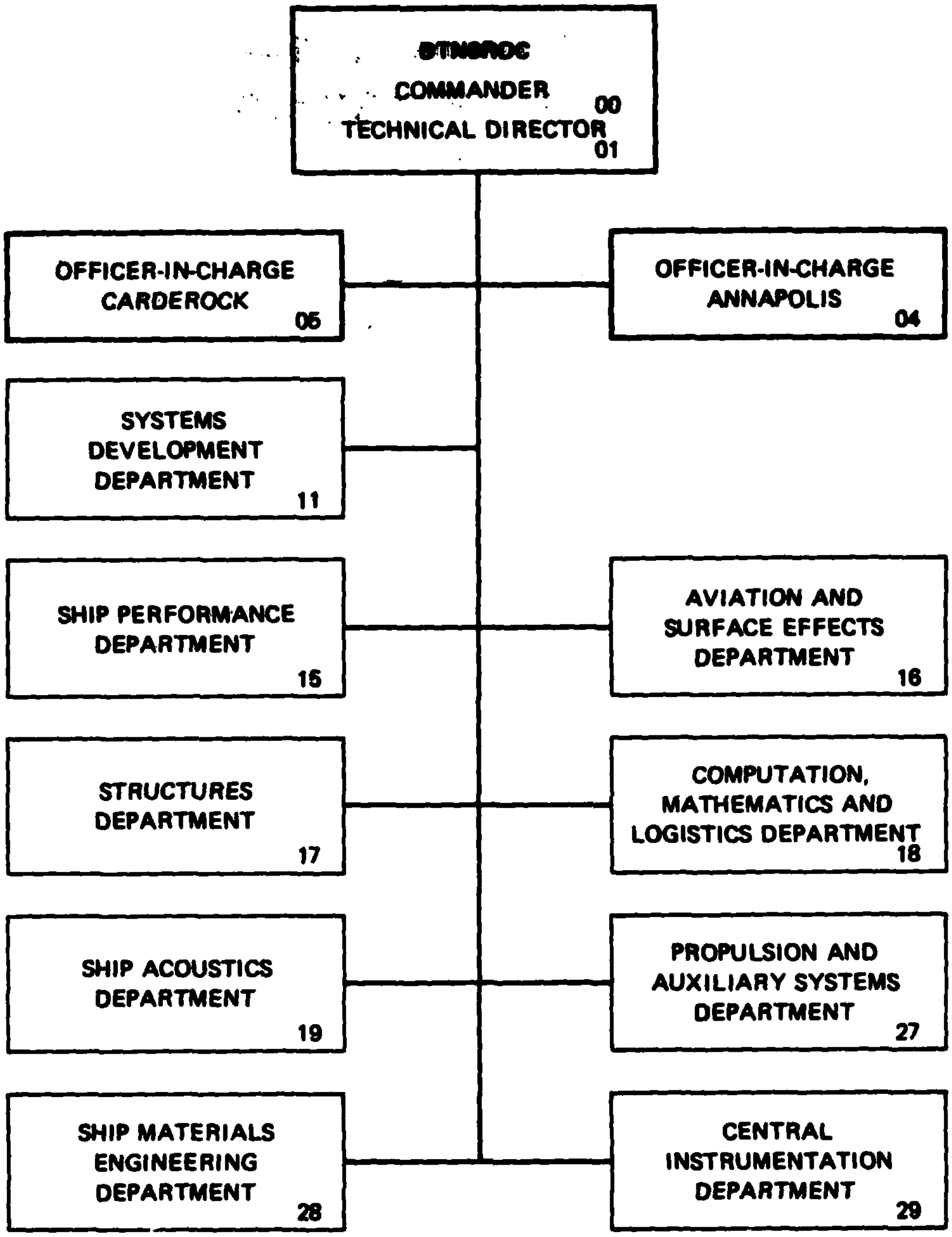

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Two epoxy-impregnated superconducting test coils, containing 0.635-centimeter electrical heaters imbedded in their windings, have been constructed to measure the minimum energy-to-quench as a function of operating current at various fixed levels of magnetic field strength. One test coil was wound with aluminum-stabilized NbTi superconducting wire and the other coil was wound with bronze matrix Nb_3Sn superconducting wire. The results of the energy-to-quench measurements are

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presented for both these test coils, and these results are compared to the previous measurements made for copper-stabilized NbTi test coils.

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LIST OF ABBREVIATIONS

Al	Aluminum
^{o}C	Degrees Celsius
cm	Centimeter
CuSn	Copper tin
d-c	Direct-current
I	Magnet operating current
Ic	Superconductor critical current
ID	Inside diameter
J	Joules
K	Kelvin
μm	Micrometer
μsec	Microsecond
mm	Millimeter
Nb_3Sn	Niobium tin
NbTi	Niobium titanium
OD	Outside diameter
T	Tesla

ABSTRACT

Two epoxy-impregnated superconducting test coils, containing 0.635-centimeter electrical heaters imbedded in their windings, have been constructed to measure the minimum energy-to-quench as a function of operating current at various fixed levels of magnetic field strength. One test coil was wound with aluminum-stabilized NbTi superconducting wire and the other coil was wound with bronze matrix Nb_3Sn superconducting wire. The results of the energy-to-quench measurements are presented for both these test coils, and these results are compared to the previous measurements made for copper-stabilized NbTi test coils.

ADMINISTRATIVE INFORMATION

The work described in this report was performed as part of the Advanced Electric Propulsion Project, Task Area SF43431503, Task 23044, and was sponsored by the Naval Sea Systems Command (SEA 05R11). The work was accomplished under Work Unit 1-2706-103 in the Electrical Machinery Technology Branch, Electrical Systems Division of the Propulsion and Auxiliary Systems Department at this Center.

INTRODUCTION

Stable and reliable superconducting magnets for use as the field windings of electric motors and generators are an important consideration for high machinery availability. Because of their compact size, ruggedness of construction, and large energy density, epoxy-impregnated superconducting magnets are being considered for the field windings of superconductive electric machinery.

A major concern with the use of fully potted and trained superconducting magnets is their stability when operating in an adverse environment. Heat energy can be imparted to the superconductor of the magnet from external mechanical disturbances, such as shock and vibration. In addition, energy stored in the magnet composite due to stress concentrations developed during magnet construction and cool-down to 4.2K* can be released in the coil winding when the coil is energized. If the heat energy released from the various possible sources is sufficiently large, the local temperature rise will drive the superconductor normal, causing the magnet to quench.

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*Definitions of abbreviations used are given on page v.

Previous work[1,2*] performed at this Center has provided stability measurement data for fully potted, superconducting test coils wound with copper-stabilized, multifilament, NbTi superconducting wire. As a continuation and extension of this work, additional stability experiments have been performed using fully potted tests coils wound with aluminum-stabilized, multifilament, NbTi, superconducting wire and test coils wound with bronze matrix (CuSn) multifilament, Nb_3Sn, superconducting wire. The NbTi/Al and Nb_3Sn/CuSn wire used in the test coils are experimental conductors fabricated to meet specifications developed by researchers at this Center. The interest in these conductors is based on the expected improvement in magnet stability that each conductor should provide compared to copper-stabilized NbTi. The A-15 compound Nb_3Sn/CuSn superconductor possesses enhanced values of critical temperature, current density, and magnetic field relative to NbTi. The aluminum matrix material of the NbTi/Al wire has improved thermal conductivity and electrical resistivity at 4.2 K compared to standard copper matrix material. Therefore, the purpose of these experiments was to measure the stability of potted test magnets wound with these conductors and to compare the results obtained to the previously measured stability characteristics of NbTi/Cu potted superconducting test coils.

SUPERCONDUCTOR FABRICATION

BRONZE Nb_3Sn SUPERCONDUCTOR FABRICATION

A cross-sectional view of the bronze matrix, multifilament, Nb_3Sn superconducting wire is shown in Figure 1. The wire is of cabled construction composed of six strands of conductor each having 240 filaments of Nb_3Sn superconductor with a twist pitch of two per 2.54 cm in a bronze matrix. The cabled conductors are reinforced with a center strand of stainless steel wire and are bonded together with a metal solder filler. The twist pitch of the cabled superconducting strands is 14 per 2.54 cm. The wire is electrically insulated with a spiral wrap of fiber glass cloth.

The fabrication of the Nb_3Sn/CuSn strands used conventional processing technology for Nb_3Sn superconductors. The general steps of this process are shown in Figure 2.

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*A complete list of references appears on page 17.

ALUMINUM MATRIX NbTi SUPERCONDUCTOR FABRICATION

A cross-sectional view of the aluminum-stabilized, multifilament, superconducting wire is shown in Figure 3. The method used to fabricate this wire involved the processes shown in Figure 4. First, a composite of multifilament, NbTi superconductor embedded in an aluminum alloy was prepared using conventional techniques. A total of 121 holes were drilled in a 76-mm-diameter by 24-mm-long, 1100 aluminum billet. Rods of Nb 53Ti, 4.8 mm in diameter, were inserted into the holes of the billet. The billet was then extruded to a extrusion ratio of 10. The extruded composite was then inserted in a high-purity (>99.995%) aluminum tube (24.4-mm OD and 19.8-mm ID) which had been fabricated by extrusion from bar stock. The NbTi-1100 aluminum core and high-purity aluminum tube were than assembled in a copper tube of 31.8-mm OD and 25.4-mm ID. The entire composite was then drawn down to its final size of 0.91-mm OD. The outer copper sheath was stripped from the wire using nitric acid, and the wire was heat-treated at 375°C for several hours and then squared to a nominal rectangular cross section of 0.635 x 0.889 mm. The wire, as received from the manufacturer, was not uniform in cross-sectional size and varied in size along the entire length of the conductor. In addition, the wire was not electrically insulated by the manufacturer. Therefore, prior to winding the test coil for the stability measurements, it was insulated by hand coating the wire with varnish electrical insulator, which resulted in a wire of highly nonuniform overall cross section along its length.

TEST MAGNET CONSTRUCTION

Two test magnets, one wound with the Nb_3Sn/CuSn wire and the other wound with the NbTi/Al wire were constructed. Both test coils, as shown in Figure 5, are epoxy-impregnated solenoidal coils. The Nb_3Sn/CuSn magnet is a five-layer coil having a total of 104 electrical turns. The input current lead and first turn of the coil as well as the output current lead and last turn of the coil are made up of one wire of Nb_3Sn/CuSn and NbTi/Cu soldered together. This was done to assure the mechanical-electrical integrity of the current leads of the coil which are subjected to mechanical abuse during the handling of the coil and installing it in the experimental setup. Similarly, the current leads and first and last turn of the NbTi/Al coil were made with NbTi/Cu wire soldered together with the NbTi/Al wire of the coil. The NbTi/Al coil is a four-layer winding having a total of 47 electrical turns. During the winding of both the Nb_3Sn/CuSn and NbTi/Al coils,

a multitapped electrical heater fabricated from constantan wire (0.339 ohm/cm) was embedded in each coil. For both coils, the heater was located between winding Layers 2 and 3 and centered along the length of each of the coils. The multitapped heater configuration allowed for the potential use of various lengths of heaters of up to 2.54 cm in length in 0.635-cm increments.

Both coils were constructed using the same methods of winding, fiber glass cloth reinforcement, and vacuum impregnation that were used to construct the NbTi/Cu coils used for previous stability measurements.[2] As shown in Figure 5, the physical size differences in these coils (NbTi/Cu coil is included for comparison) results from the differences in overall cross-sectional size of superconducting wire used for each coil.

EXPERIMENTAL METHOD

To measure the stability of each of these test coils at magnetic flux densities of 3 to 5T, each coil was placed in the inner bore of a background magnet, as shown in Figure 6. The superconducting, NbTi, background magnet has an inside diameter of 19.4 cm, an outside diameter of 24.0 cm, and is 9.4 cm in length. Each test magnet, when installed for measurement, is concentrically positioned at the mid-length of the inner bore of the background magnet.

For the experiments to measure the energy-to-quench, the assembly of the test coil and background coil was placed in a liquid helium, cryogenic dewar and cooled from room temperature to 4.2 K. After the background and test magnets reached their superconducting state, they were energized to predetermined operating currents using separate power supplies, as shown in Figure 7.

Prior to performing the energy-to-quench experiments the critical current of each test coil was measured at different levels of magnetic field strength. The results of the measurements are shown in Figure 8.

The objective of the experiment was to measure the minimum energy required to quench the Nb_3Sn/CuSn and the NbTi/Al magnets for various levels of fixed field strength and for various values of test coil operating current. Therefore, for the experiments, the background magnet was energized to provide a constant background field level, and the coil under testing was energized to an operating current that was a desired percentage of its critical current at the background level.

To quench the test coil with a known amount of electrical energy, a pulse generator and power amplifier system, as illustrated in Figure 7, was used to

deliver a single pulse of known electrical energy to the resistor heater embedded in the test coil. A dummy resistor approximately equivalent to the heater resistance was used to allow measurement of the amplitude and width of the electrical pulse with a calibrated oscilloscope prior to applying the pulse to the heater. The actual test procedure involved maintaining the pulse width at a fixed value of 100 to 300 μsec and adjusting the pulse amplitude to obtain the minimum energy required to quench the coil. Measurements previously reported by Superczynski[2] showed that energy-to-quench remained constant over a pulse width of 10^2 to 10^4 μsec. For each run of the experiment, the amplitude of the constant width pulse was initially set to a value estimated to be less than that needed to quench the magnet. The pulse amplitude was then increased in small increments until the test magnet quenched.

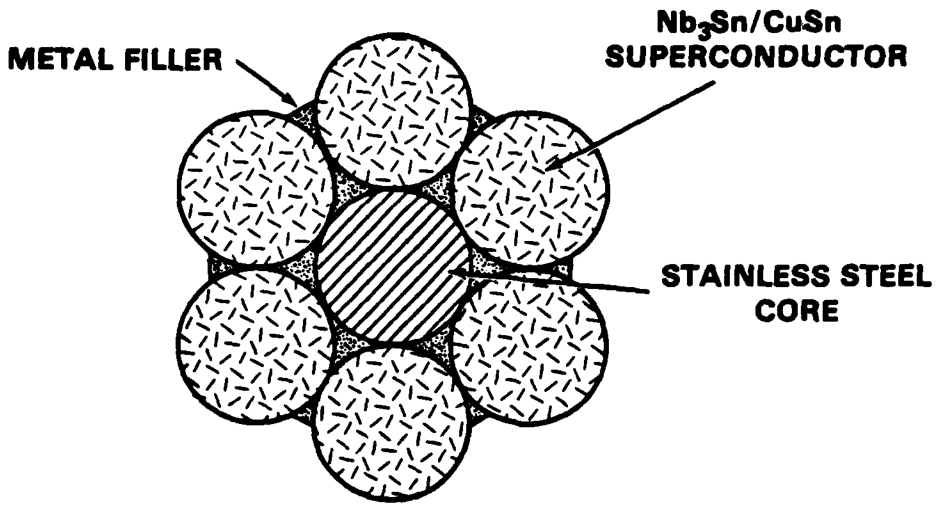
DISCUSSION OF RESULTS

The results of the measurements of the minimum energy required to quench the Nb_3Sn/CuSn and the NgTi/Al test coils are shown in Figure 9. In the figure, energy-to-quench the test coil, using a 0.635-cm heater, is plotted as a function of the ratio of the test coil operating current to its critical current (I/Ic) for the magnet field strengths shown. For purposes of comparison, a plot of previous measurements[2] of the energy-to-quench a NbTi/Cu test coil using a 0.635-cm heater is shown in Figure 9. The results show that the energy-to-quench as a function of I/Ic for both the Nb_3Sn/CuSn and NbTi/Al coils is greater than that to quench the NbTi/Cu coil. In the I/Ic region of 0.3 to 0.9, the energy-to-quench the Nb_3Sn coil is approximately a factor of 3 (I/Ic = 0.3) to a factor of 10 (I/Ic = 0.9) greater than the energy-to-quench the NbTi/Cu coil. For the NbTi/Al coil, the energy-to-quench is approximately a factor of 30 greater than that of the NbTi/Cu coil over the I/Ic range of 0.3 to 0.9. But, as can be seen, the measured results for both the Nb_3Sn/CuSn and NbTi/Al coils do not show a sharp decrease in the magnitude of the energy-to-quench at the higher value of I/Ic (0.9 and greater) as would be expected. Since there is insufficient data to indicate that the long length current and magnetic field characteristics of the Nb_3Sn/CuSn superconducting wire or the NbTi/Al, as shown in Figure 8, agree with their short sample wire characteristics, the I/Ic values used in Figure 9 may not be correct. Because of possible nonuniformity in the cross-sectional area and filament size of the Nb_3Sn/CuSn wire and the known construction nonuniformity of the NbTi/Al wire, the critical current of each wire at the heater location could be greater than that

measured for the entire coil winding. If this is the case, the actual I/Ic values would be less than those shown in Figure 9, and the energy-to-quench plots for both coils would shift to the left. This would, therefore, indicate that measurements were not actually obtained at the higher I/Ic values where the energy-to-quench is expected to rapidly decrease. Another observation from the data results shown in Figure 9 is that the measured values of energy-to-quench for the Nb_3Sn/CuSn and NbTi/Al test coils were not dependent upon the magnetic field strength. This differs from the results obtained for the NbTi/Cu test coil, which indicated that high field magnets are less stable than low field magnets. The reason for this difference is not known.

CONCLUSIONS

The measurements of the energy-to-quench a potted test coil wound with Nb_3Sn/CuSn superconducting wire and a potted test coil wound with NbTi/Al wire show that both these magnets are more stable compared to coils wound with NbTi/Cu wire. The Nb_3Sn/CuSn test coil required values of energy-to-quench over an I/Ic range of 0.3 to 0.9 of a factor of 3 to 10 more than that of a NbTi/Cu test coil. The NbTi/Al test coil required values of energy-to-quench of a factor of 30 more than a NbTi/Cu test coil over an I/Ic range of 0.3 to 0.9. Possible nonuniformities in the construction of the Nb_3Sn/CuSn wire and the known nonuniformities in the construction of the NbTi/Al wire could modify the results presented due to the possibility that the critical current value of the wire at the heater location of each coil can be higher than the measured value of each coil. The results presented are also based on measurements made with only one coil of each type of wire. A larger data base is needed, with measurements from several coils wound with Nb_3Sn/CuSn and NbTi/Al wire, to verify the results presented.



OVERALL DIAMETER	0.457 mm
STRAND SIZE	0.152 mm
CuSn/SUPERCONDUCTOR RATIO	~2.5 TO 1
NO. OF FILAMENTS (6 X 240)	1440
FILAMENT DIAMETER	~6 μm

Figure 1 - Cross-Sectional View of $Nb_3Sn/CuSn$ Superconducting Wire

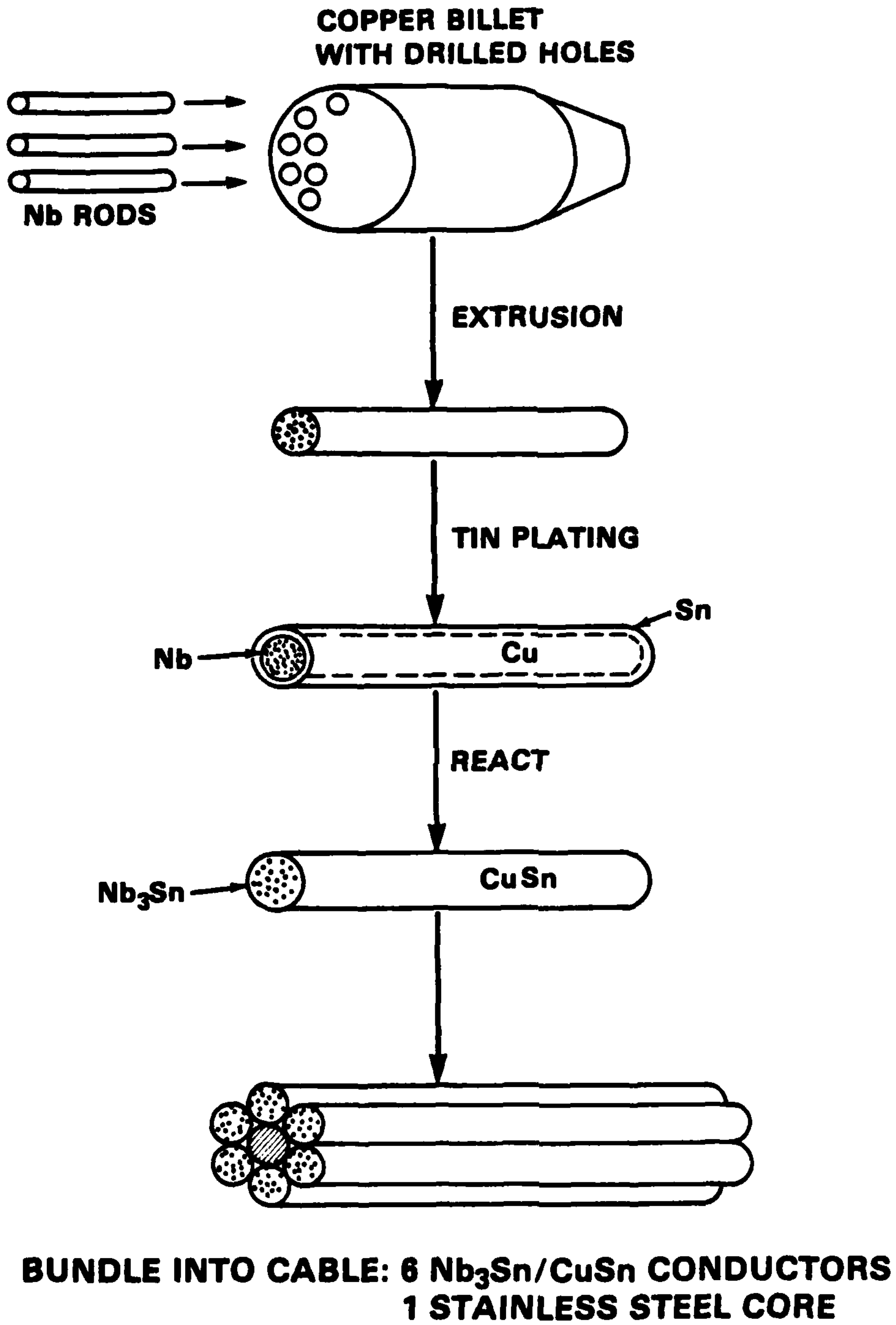
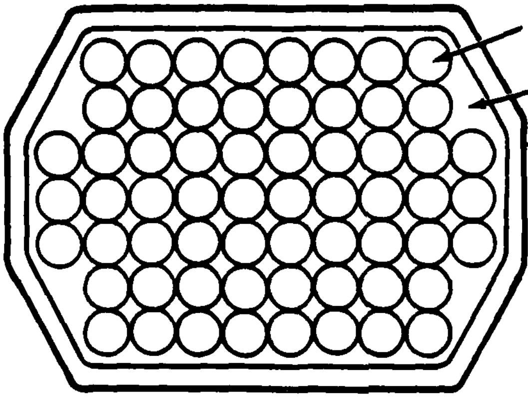


Figure 2 - Nb_3Sn/CuSn Superconducting Wire Fabrication Process



CROSS-SECTIONAL SIZE	0.635 m × 0.889 mm
Aℓ/SUPERCONDUCTOR RATIO	2.5 TO 1
NO. OF FILAMENTS	121

Figure 3 - Cross-Sectional View of NbTi/Aℓ Superconducting Wire

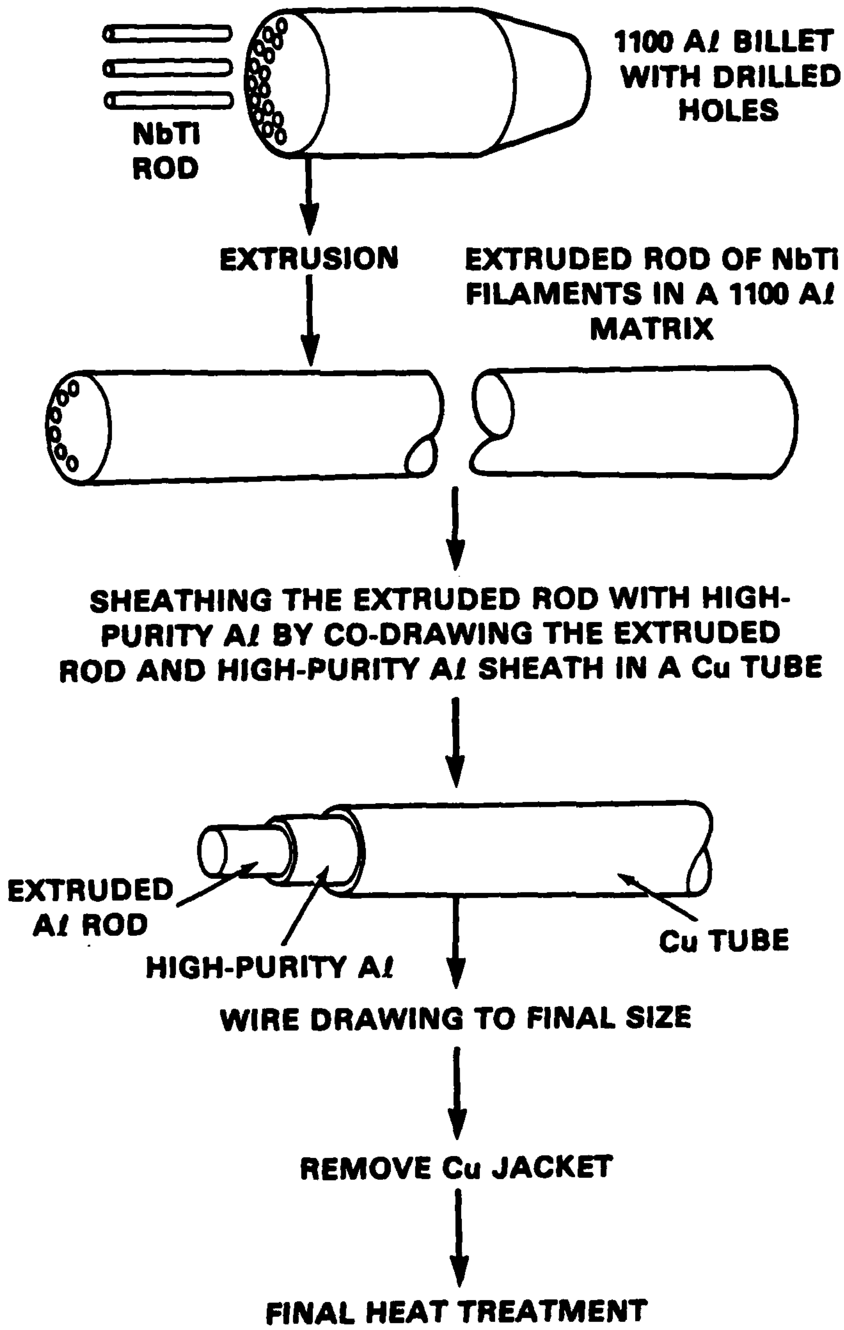
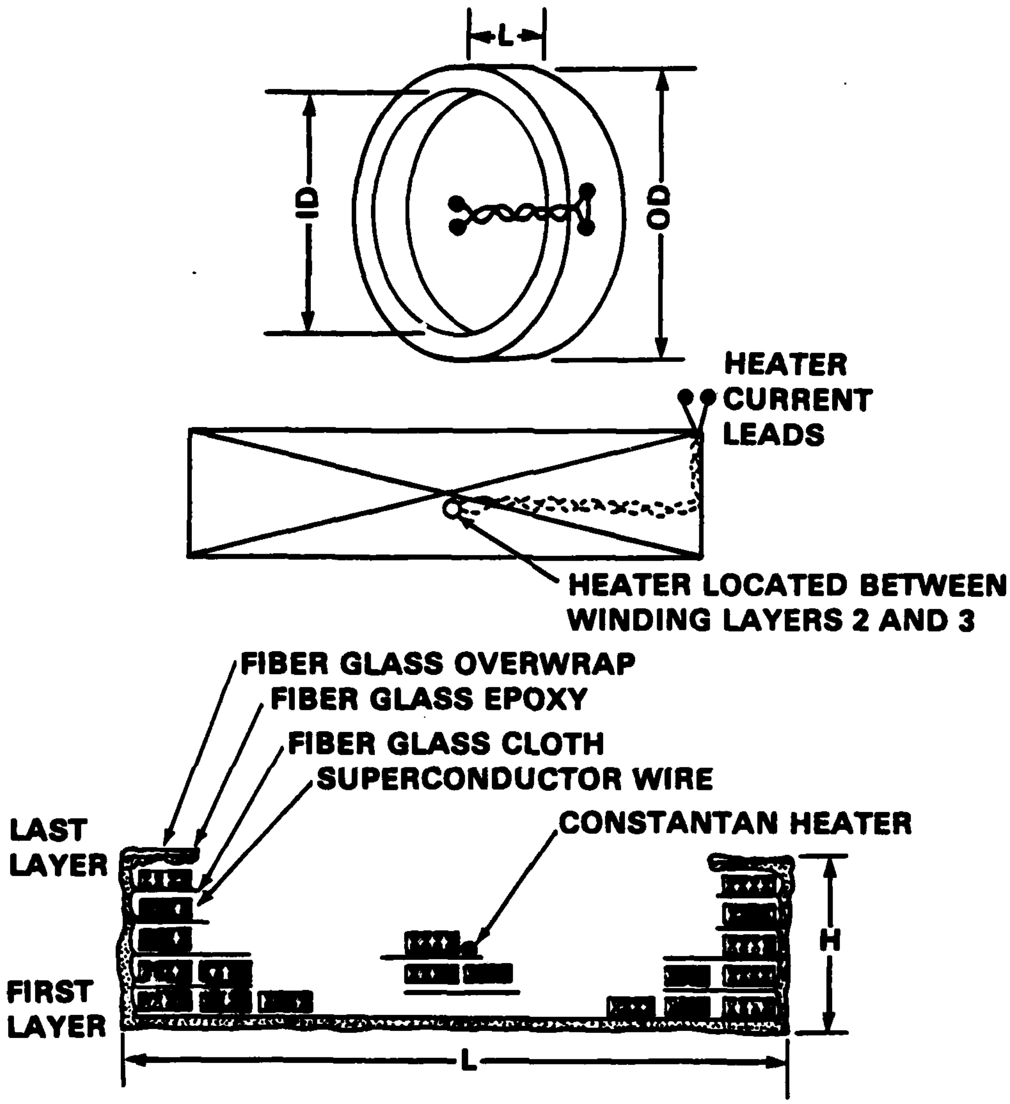


Figure 4 - NbTi/Aℓ Superconducting Wire Fabrication Process



TEST COIL	ID (cm)	OD (cm)	L (cm)	H (cm)	N
$Nb_3Sn/CuSn$	18.00	18.81	1.40	0.406	104
NbTi/Al	18.00	19.00	1.40	0.50	47
NbTi/Cu	18.00	18.76	1.40	0.38	88

Figure 5 - Superconducting Test Coil Construction and Heater Location

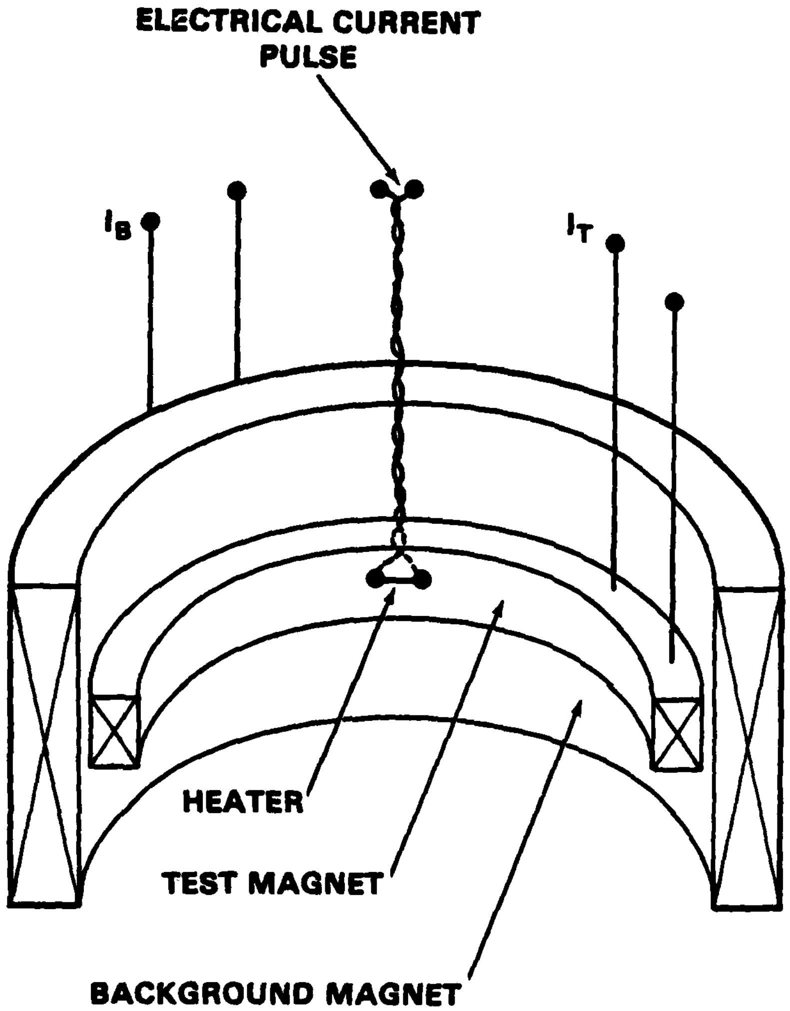


Figure 6 - Magnet Assembly for Energy-to-Quench Measurements

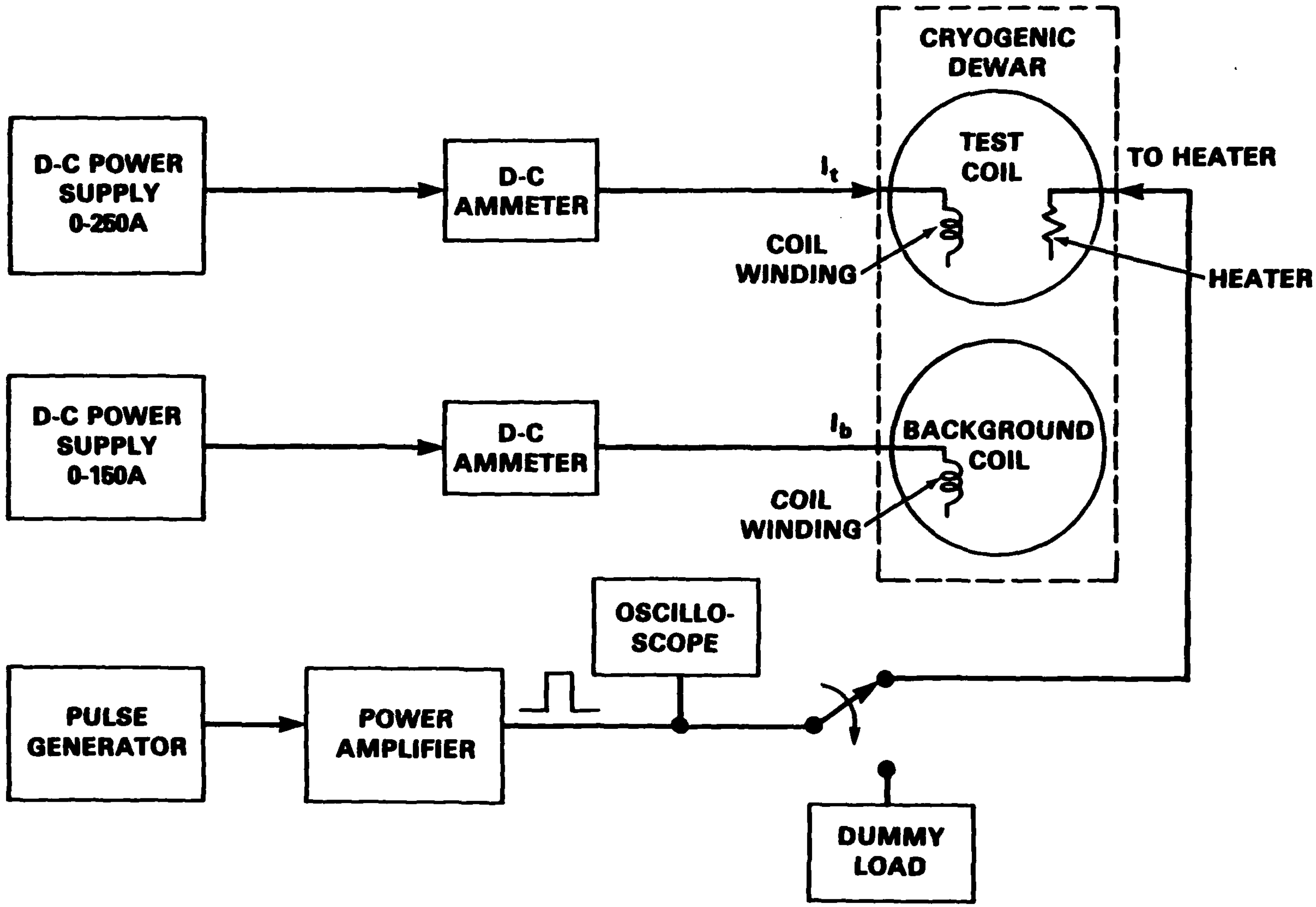


Figure 7 - Experiment Instrumentation and Power Supply Connection Diagram

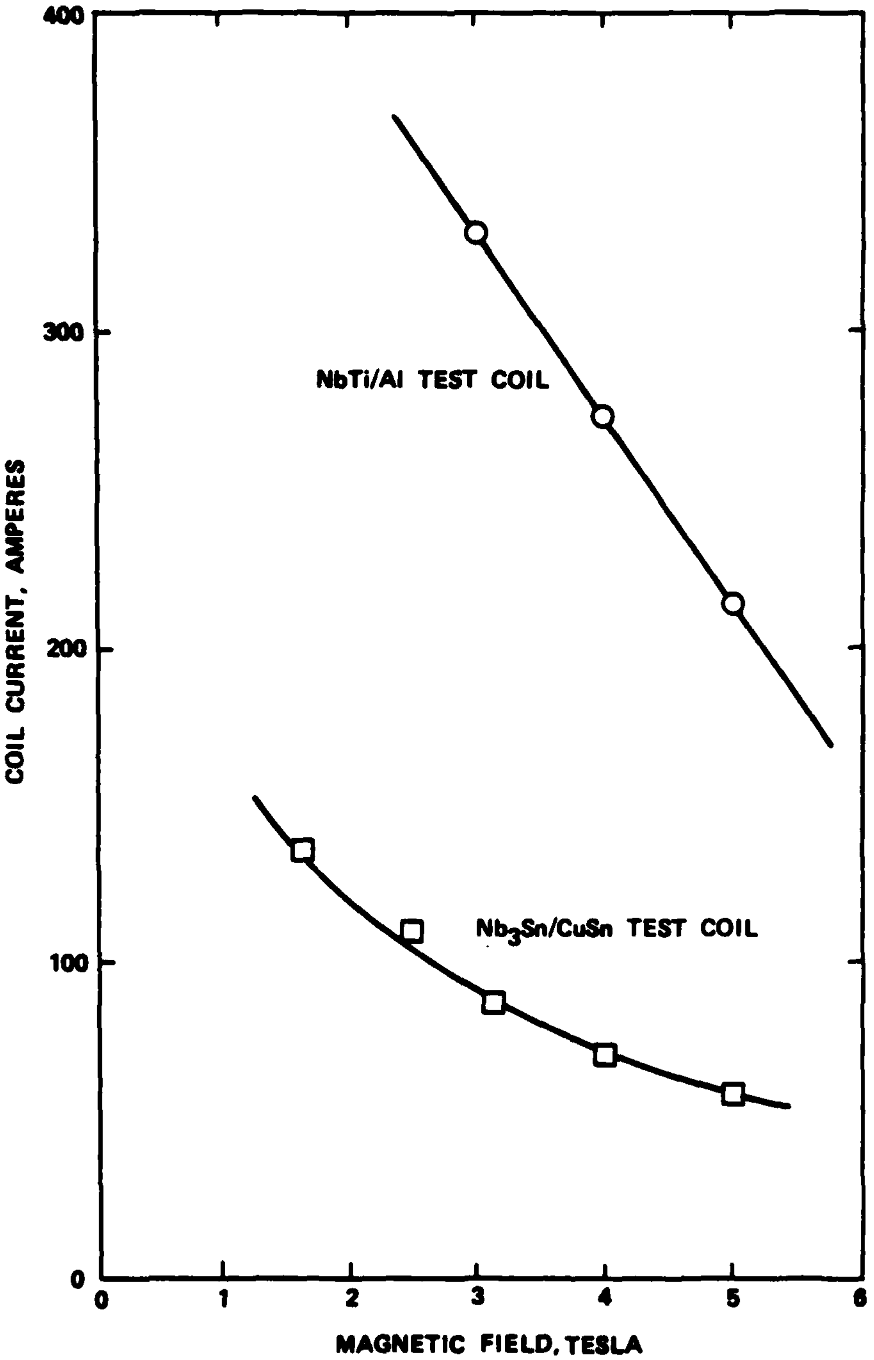


Figure 8 - Critical Current (I_C) Measurement Results for the NbTi/Aℓ and Nb_3/CuSn Test Coils

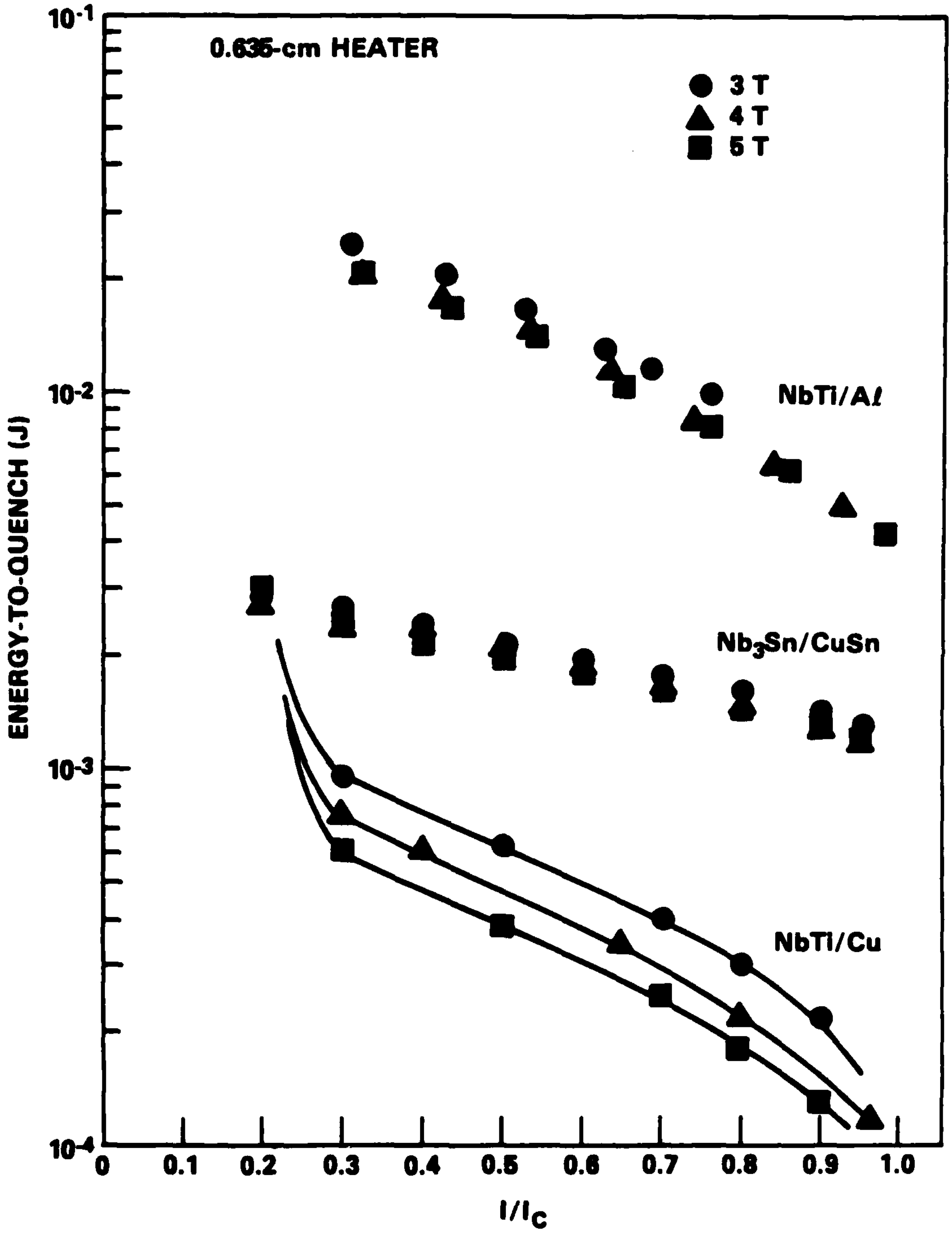


Figure 9 - Energy-to-Quench Versus I/I_C for Nb_3Sn/CuSn, NbTi/Aℓ, and NbTi/Cu Test Coils

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